APPLICABILITY OF AMBIENT TEMPERATURE RELIABILITY TARGETS FOR APPRAISING STRUCTURES EXPOSED TO FIRE

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ABSTRACT

Reliability based methods are at the core of Eurocode structural design. Partial load factors, combined with material safety factors, are derived from First Order Reliability Methods (FORM) with the intention of ensuring that structural elements or sub-frame assemblies have an appropriately low probability of failure. The acceptable probability of failure is informed by the likely consequences, with societal risk expectations influencing what level of confidence must be achieved in a design solution.

Fire development and subsequent structural response depend upon numerous factors, invariably featuring a high degree of uncertainty. Whilst permitted within performance-based frameworks, and supported by design codes, the appraisal of structural response in fire in a deterministic manner is challenging given the plethora of sources of uncertainty that exist.

It has become increasingly common practice for UK practitioners to adopt reliability based assessments for appraising the fire resistance requirements for structural elements. The acceptance criteria for such analyses are often informed by the work undertaken in the development of BS 9999, which defines an 'overall reliability target' as a function of height and use. These reliability targets are then augmented by consequence factors to account for variances in evacuation mode, i.e. buildings with a prolonged evacuation regime are afforded a higher consequence classification. The cons of such an approach come in situations where: (a) a building is mixed use (as is often the case), (b) height is not an appropriate proxy for the quantification of probability of fire occurrence nor consequence of failure, and/or (c) the building is not in the UK.

The paper discussed how ambient temperature target probabilities of failure, such as those based on cost optimisation or documented in EN 1990, can be used to inform fire resistance design solutions. The spectrum of fire severities expected within a simple steel structure office building are appraised via Latin Hypercube Sampling (LHS). Fire resistance solutions are reviewed for different consequence classes, with the results contrasted against established reliability methods and prescriptive conventions. The conclusions suggest that ambient reliability targets have relevance. However, it may be preferable to define two reliability targets for structural performance for: (1) during evacuation, and (2) longer term probability of failure (burn-out).

1. INTRODUCTION

Performance based structural fire engineering design implicitly requires the approximation of a safety goal and a means of estimating if it has been fulfilled. Often, this process is deterministic. That is, the engineer selects a series of inputs and properties that, when applied within various models (fire dynamics, heat transfer and / or structural response), inform design solutions that are deemed to be adequate. The design solution may be premised on the selection of onerous inputs from the ranges / distributions expected (a reasonable worst case) or it may be afforded an appropriate factor of safety. Irrespective of the means, the acceptance of any resulting solution can only be premised upon one of two grounds: (a) adequate experience / precedent, or (b) a very high degree of conservatism. In neither case is the safety target explicit, nor are the grounds for accepting a design solution universally valid. For instance: (a) infers that there is a compatibility between the design being developed and those that exist for which there is bountiful experience (i.e. common situations), and (b) implies that the consequences are comprehensible and, as a result, an estimation of the required safety margin can be made. In either case it can be summarised that deterministic assessments only have validity for fairly straightforward, low complexity, proportionally low consequence of failure structures. For more complex, unusual or high consequence structures, there is a need to explicitly define safety targets and develop fire resistance solutions capable of fulfilling them. These explicit safety targets could be founded upon one of three common ambitions: (a) fulfilling a minimum societally accepted robustness target, (b) ensuring that a minimum societally accepted robustness target is fulfilled, whilst optimising investment in safety measures over a building's life, or (c) achieving an explicit resilience target.

Both (a) and (b) principally purport to address life safety, whilst (c) sits within the domain of property / asset protection. All targets necessitate the need for stochastic variables to be identified and for some form of Probabilistic Risk Assessment (PRA) to be undertaken. This paper draws upon experiences and methods developed within structural engineering to review how they might be applied to inform life safety targets for structures exposed to fire. It also briefly summarises common safety targets currently employed in structural fire engineering applications.

2. SAFETY TARGETS IN STRUCTURAL ENGINEERING

A number of differing means of determining the safety target for general structural design are present in the literature and / or are subject to widespread application. These are briefly summarised below.

2.1 EUROCODE - BASIS OF DESIGN

Reliability based methods are at the core of Eurocode structural design. Partial load factors, combined with material safety factors, are derived from First Order Reliability Methods (FORM) with the intention of ensuring that structural elements or sub-frame assemblies have an appropriately low probability of failure. Implicitly, for a design following EN 1990 [1] and the partial factors in Annex A, the safety target is 1.3 x 10^{-6} for a one year reference period. That is, all design solutions should achieve a reliability index (β) of 3.8 in a building's conceptual design life (50 years).

Annex B offers additional context to Annex A in support of PRA applications, whereby structures are grouped into consequence classes and afforded differing safety targets, i.e. as per the below for a one year reference period.

- Reliability class 1 – low consequences – buildings where people rarely enter – β = 4.2;
- Reliability class 2 – Medium consequences – e.g. a typical office buildings – β = 4.7; and
- Reliability class 3 – High consequences – e.g. high rise buildings – β = 5.2.

2.2 JCSS 2001 – COST OPTIMISATION

The Joint Council on Structural Safety (JCSS) provide tentative failure rates as a function of safety measure investment and failure consequences [2]. For the more typical case, i.e. where investments in safety measures are moderate, the following safety targets are given:

- Minor failure consequences – β = 3.7;
- Moderate failure consequences – β = 4.2; and
- Large failure consequences – β = 4.4.

Consequences are classified according to the ratio of total costs (i.e. construction costs plus direct failure costs) and construction costs. Given this, the failure rates cannot be applied in a life safety context without a separate consideration of societal risk / acceptance.

2.3 THE LIFE QUALITY INDEX (LQI)

LQI is effectively a derivative of cost optimisation, with investments in safety measures balanced against the willingness of society to invest in those safety measures.

The philosophy behind the LQI is that the preference for society to invest in safety measures is influenced by life expectancy at birth, GDP and the relative proportions of working time vs. leisure time. It is, in essence, a lower boundary condition for private cost optimisation (see Figure 1 below).

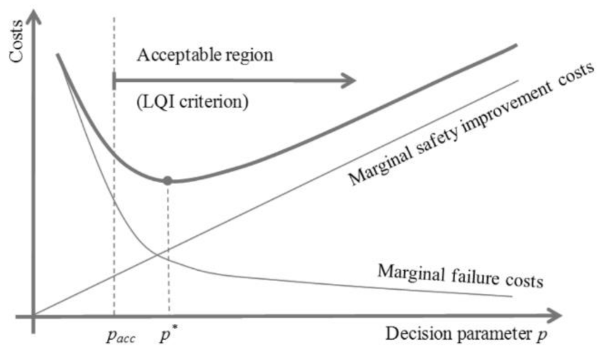

Figure 1 – LQI as a boundary condition to monetary optimisation [3]

The safety target is derived in consideration of marginal lifesaving costs, relative cost of safety measures (i.e. relative to the total construction costs) and the consequences of failure (fatalities). Further background and application examples can be found in Fischer & Faber [3] and ISO 2394 [4].

3. SAFETY TARGETS IN STRUCTURAL FIRE ENGINEERING

Limited comparable literature exists in relation to deriving safety targets for fire exposed structures.

3.1 BACKGROUND TO BS 9999

The broad aim of the fire resistance guidance in BS 9999 [5], is the delivery of a consistent level of risk across all building types and heights. For this to be achieved, as the frequency of fires and consequence of failure increases, the reliability of the fire resistance system must also increase. This manifests in the tabulated guidance through increases in fire resistance with height.

In the process of developing the ventilation-based fire resistance tables of BS 9999, the then committee [6] sought to explicitly quantify the fire resistance life safety goal in terms of the number of fully developed (or significant) fires that the fire resistance system (inclusive of active and passive components) should resist as an overall proportion of the range of fully developed (or significant) fires that might occur. In doing so, a number of idealisations were made to conform to the current UK prescriptive framework:

- The frequency with which fires occur is directly influenced by a building's area. Buildings of greater height typically feature a greater number of storeys and, thus, area. Therefore, the frequency of fire occurrence for a given building could be idealised as being proportional to height;
- Should a significant fire occur, there is a reliability associated with the fire resistance system's ability to resist failure. Specifically, this relates to the robustness of an isolated element, not that of a structural system; and
- If a fire occurs and it leads to failure of a building's structural element(s), the consequence for those in (or in the vicinity of) the building is proportional to height. This is on the premise that buildings of greater height have greater area (and, thus, occupants) and that taller buildings have a greater impact on surrounding neighbourhoods, should a building suffer collapse.

The resulting relationship between target risk and building height underpinning BS 9999 is, therefore, proportional to height squared. Figure 2 below shows the corresponding relationship between target reliability and height for an office building. It should be noted that the simplistic risk correlation presented by Kirby, et. al., is anchored to the prescriptive guidance within Approved Document B (ADB) [7], such that the 80th percentile corresponds with an office building 18m in height.

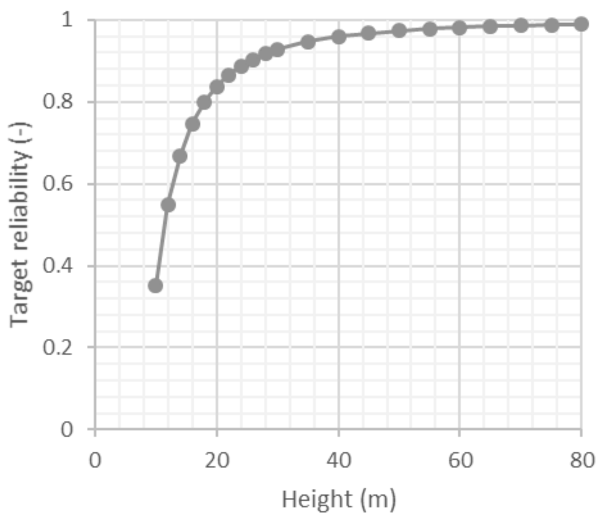

Figure 2 – Relationship between height and target reliability implicit within BS 9999 for an office

3.2 THE NFSC

In the case of the Natural Fire Safety Concept (NFSC) Valorisation Project [7], which subsequently informed the development of EN 1991-1-2 [8], a constant explicit probability of failure was chosen (7.23 x 10^{-5} per conceptual building life (50 years), or 1.3 x 10^{-6} for a one year reference period) corresponding to the same criterion for general / ambient temperature (ULS) structural design. The Valorisation Project does note that an accidental condition, such as fire, can be distinguished from normal service conditions, as a function of evacuation mode and, thus, consequence of failure. Example values from the

NFSC are shown below. The NFSC permits the derivation of a negative reliability index (β) where measures are put in place to prevent the development of a significant fire, i.e. through highly effective fire safety management. This could hypothetically mean that fire protection may be omitted on the basis of ignition control measures.

Table 1 – NFSC element safety targets by building type (1 year reference period)

Evacuation	Acceptable Probability of Failure
Typical, i.e. simultaneous	1.3×10^{-4}
Prolonged, e.g. phased or progressive	1.3×10^{-5}
Unlikely, e.g. super-high-rise	1.3×10^{-6}

4. ELEMENT FAILURE PROBABILITIES FOR A SIMPLE FIRE EXPOSED STEEL STRUCTURE

To assess the relevance of the safety targets discussed in Section 2, a pilot study has been developed for a straightforward steel building. The relevant inputs and considerations are discussed below.

4.1 TRIAL BUILDING(S) & SOLUTIONS

The building employed in the pilot study is a simple monolith, used as an office in the UK. On plan, it is assumed to be 500 m^2 in net internal area (NIA), with glazing to all elevations from floor to ceiling. The floor to ceiling height is 3 m.

Each floor is a fire compartment and compartments can be stacked to form buildings of different heights and, thus, consequence classes. The cases considered are:

- Case A – Low-rise – ground plus one < 5.0 m in height;
- Case B – Low-Mid-rise – ground plus six < 18.0 m in height;
- Case C – Mid-rise- ground plus ten < 30.0 m in height; and
- Case D – High-rise – ground plus twenty > 30.0 m in height.

The structure is assumed to be steel and the element subject to appraisal herein is a beam, formed from S355 steel, with a section factor of 150 m^{-1} and a limiting temperature of 620°C. For the given cases A – D, the corresponding prescriptive fire resistance solution according to Approved Document B is given in Table 2. Alongside this, the thickness of a notional insulation material required to prevent a temperature rise above that of the limiting temperature at the target fire resistance period is also given. This has been determined according to BS EN 1993-1-2 [10]. It should be noted that the solution for Case D includes sprinkler protection alongside the insulation thickness corresponding with 120 minutes structural fire resistance. For completeness, insulation properties are given in Table 3 also.

Table 2 – FR solutions & insulation thicknesses

Case	FR Solution (min)	Insulation thickness (mm)
A	30	6
B	60	14
C	90	21
D	120	27

Table 3 – Insulation properties

Property	Metric	Unit
Conductivity	0.2	W/m.K
Specific Heat	1,700	J/kg.K
Density	800	kg/m^3

4.2 PROBABILISTIC FACTORS LEADING TO A FIRE INDUCED STRUCTURAL FAILURE

The events that lead-up to a potential structural failure in the event of fire all have a probability of occurring. In the first instance a fire must develop (p_{ig}), subsequently there must be a compound failure of early intervention by the occupants ($p_{f,u}$), active measures ($p_{f,s}$) and the fire brigade ($p_{f,fb}$). From this point, the fire may become fully developed (or significant).

Allied to this, the structure ($P_{f,fi}$) must be sufficiently affected by the fully developed fire such that it undergoes damage and, potentially, fails (i.e. $P_{f,1}$) as a result of fire. This process can be shown via an event tree, as per Figure 3 proposed by Van Coile, et. al [11]. Within this, two domains have been further identified, the “event instigation” and “response” domains.

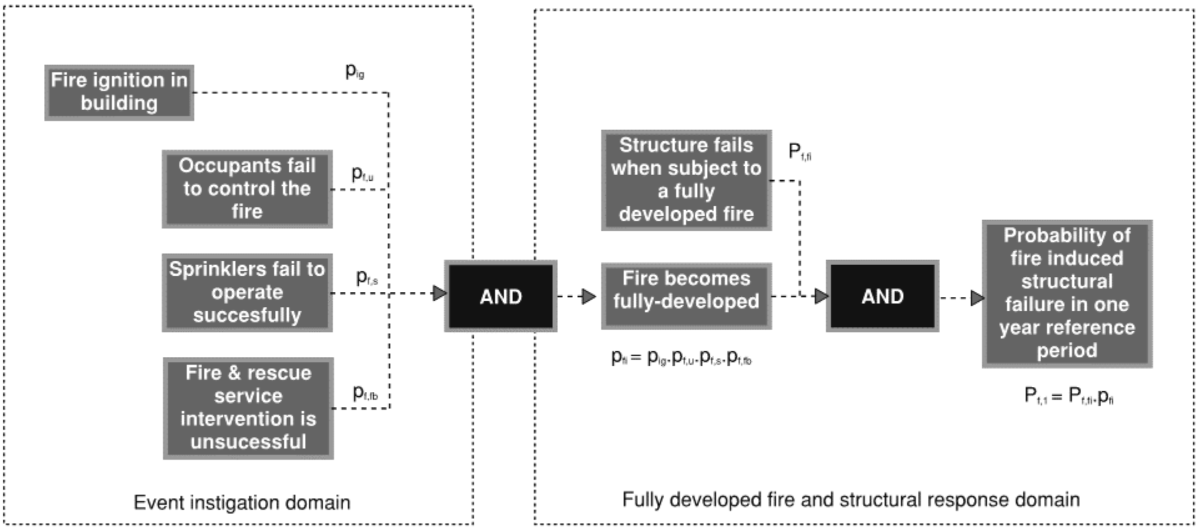

Figure 3 – Stochastic factors leading to a fire induced structural failure [11]

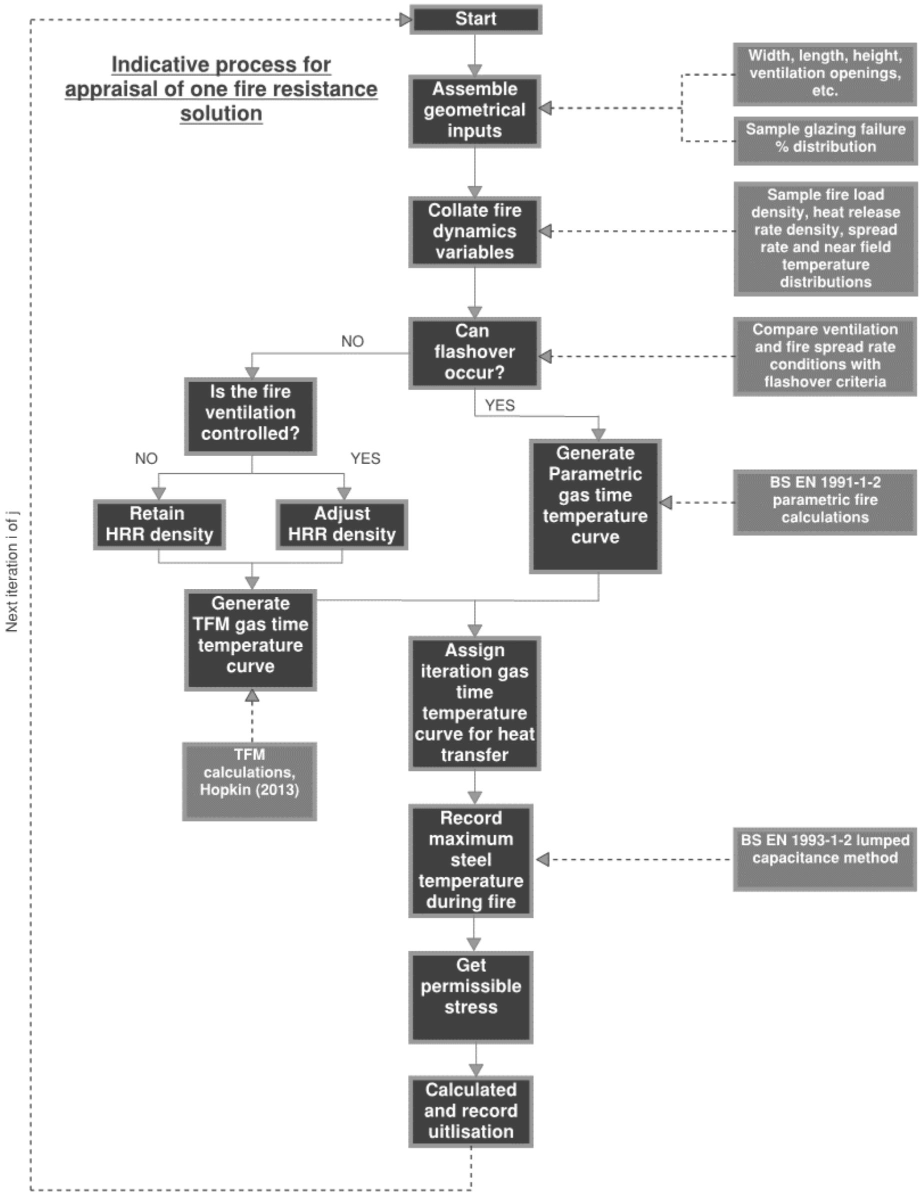

Figure 4 – Flow chart summarising one iteration of the Monte Carlo analysis

4.3 STOCHASTIC VARIABLES

For the purposes of analysis herein, the sources of uncertainty are limited to the thermal domain. Specifically, factors influencing how a fire might develop. Depending upon the choice of fire model, different variables (inputs) are relevant. The adopted stochastic variables are summarised below.

Table 4 – Stochastic fire inputs

Input	Distribution	Comment
Fire load density (MJ/m^2)	LN	Mean = 420 Std. = 126
Heat release (kW/m^2)	C	290
Glazing failure (%)	U	Range = 5 - 100
Near field temperature (°C)	N	Mean = 1,050 Std. = 64.5
Spread rate (mm/s)	U	Range = 5 – 19

LN – Log Normal, C – Constant, U – Uniform, N – Normal

The likelihood of a fire occurring is also a source of uncertainty. Within the event instigation domain, there is firstly the likelihood that a fire occurs. Subsequent to this, there are numerous interventions that are possible which prevent the fire from becoming significant. The basic likelihood values within the NFSC concept are adopted for an office, i.e. a per annum fire probability of between 2 – 4 x 10^{-7} per m^2. These relate to cases where occupants and the fire brigade have a 'typical' chance of successful intervention. The median value is adopted in arriving at Section 4.7, i.e. 3 x 10^{-7} fires per annum per m^2.

For cases where sprinklers are considered, a failure probability of 10% is adopted. This reduces the significant fire likelihood by an order of magnitude.

4.4 SAMPLING PROCESS AND METHODOLOGY

With reference to Figure 3, in the "event instigation domain" the likelihood of a significant fire occurrence, i.e. one whereby none of the occupants, fire brigade or active measures (where relevant) have successfully prevented a fire from becoming fully developed, is estimated based on the proposals documented in the NFSC Valorisation project (discussed in 4.3). From this point, and within the response domain, fires will manifest in different ways / severities, which elicit different types of structural element response.

Figure 4 provides an overview of the processes involved in defining a design fire and assessing whether or not the design fire leads to a structural element failure. The figure concerns one model realisation. The iterative sampling process is repeated for different fire resistance solutions, e.g. 30, 60 and 90 minutes. Typically, the accepted solution would be the optimal protection thickness that ensures the probability of failure is less than a defined safety target.

4.5 FIRE MODELS

Within Figure 4, two fire models are apparent (Figure 5). One relates to a travelling fire [12], the other a Eurocode parametric fire. Decision metrics are presented within the process flow chart which define the circumstances under which different fire models are deployed. A key distinction in the travelling fire method employed herein compared to others is that of the influence of ventilation. That is, the travelling fire adopted can be subject to a ventilation controlled limit.

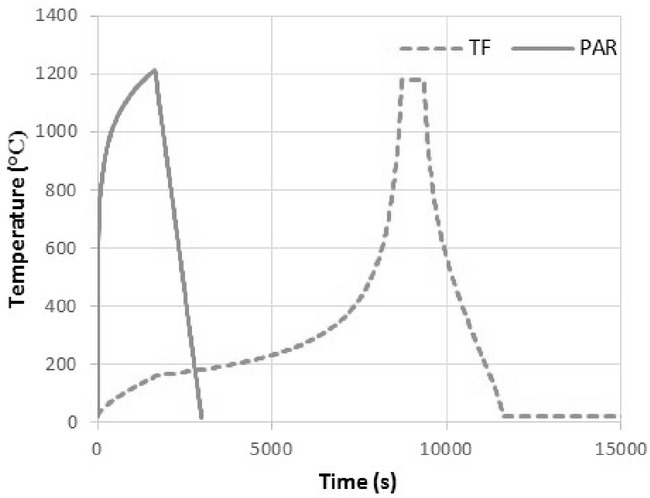

Figure 5 – Fire model types – TF – Travelling Fire vs. PAR – Parametric Fire

4.6 SEVERITY / FAILURE METRIC

The study presented herein does not purport to address the 'failure' of a structural system.

It focusses upon the probability of failure of an isolated element when afforded specific protection solutions. Therefore, a critical temperature based criteria is adopted to assess 'failure'. The metric adopted is a simple utilisation based concept, which allows for future incorporation of other uncertainties (such as yield strength and applied action), i.e.

$$\mu = \sigma_a / k_y f_y$$

With μ the utilisation (-), σ_a the applied stress, and k_y the temperature reduction factor for the yield strength f_y.

The applied stress is chosen such that the ambient utilisation yields a limiting temperature of 620°C. A utilisation in exceedance of unity denotes 'failure'.

4.7 LHS RESULTS

For 10,000 Latin Hypercube Samples per fire resistance design solution, Figure 6 presents the relationship between element utilisation and the probability of exceeding a given utilisation, when subject to natural fires. Each curve represents a fire resistance (protection) solution.

From this, failure probabilities can be deduced by determining the points at which the utilisation is in exceedance of unity, for a given fire resistance solution. The results are summarised in below.

Table 5 – Element failure probabilities as a function of fire resistance solution (one year reference period)

Case	Solution	P(f)
A	FR30	$\approx 1 \times 10^{-4}$
B	FR60	$\approx 1 \times 10^{-5}$
C	FR90	$\approx 3 \times 10^{-6}$
D	FR120 + sprinklers	$\approx 1 \times 10^{-7}$

5. COMPARISON WITH ESTABLISHED AMBIENT SAFETY TARGETS

The results of Section 4.7 are contrasted with the safety targets discussed in Sections 2 and 3 with intent of establishing the consistency between safety targets presented in the literature for structural (fire) engineering, and those that appear to be inherent within Approved Document B.

5.1 TENTATIVE CONSEQUENCE GROUPING

For the purpose of appraising the cases investigated (A to D), each case is grouped (tentatively) into a consequence class. This is proposed as follows:

- Case A – Nominal (minor) consequences;
- Case B – Low consequences;
- Case C – Moderate consequences; and
- Case D – High consequences.

5.2 COMPARISON WITH AMBIENT SAFETY TARGETS

The Latin Hypercube study results for different fire resistance solutions can be contrasted with tentative consequence groupings in Section 5.1 and the differing means of deriving safety targets in Section 2 to assess the relevance of these methods for structural fire design.

Based solely upon crude cost optimisation after the JCSS, the element fire resistances required as a function of consequence class is as follows:

(a) Minor consequences – target failure probability $\approx 1 \times 10^{-4}$ – 30 minutes fire resistance;
(b) Moderate consequences - target failure probability $\approx 1 \times 10^{-5}$ – 60 minutes fire resistance; and
(c) High consequences - target failure probability $\approx 5 \times 10^{-6}$ – 90 minutes fire resistance.

In contrast, the corresponding figures for Annex B of EN 1990 are as follows:

(a) Reliability class 1 (low consequences) – target failure probability $\approx 1 \times 10^{-5}$ – 60 minutes fire resistance;
(b) Reliability class 2 (Moderate consequences) - target failure probability $\approx 1 \times 10^{-6}$ – 120 minutes fire resistance; and
(c) Reliability class 3 (High consequences) - target failure probability $\approx 1 \times 10^{-7}$ – 120 minutes fire resistance, plus sprinklers.

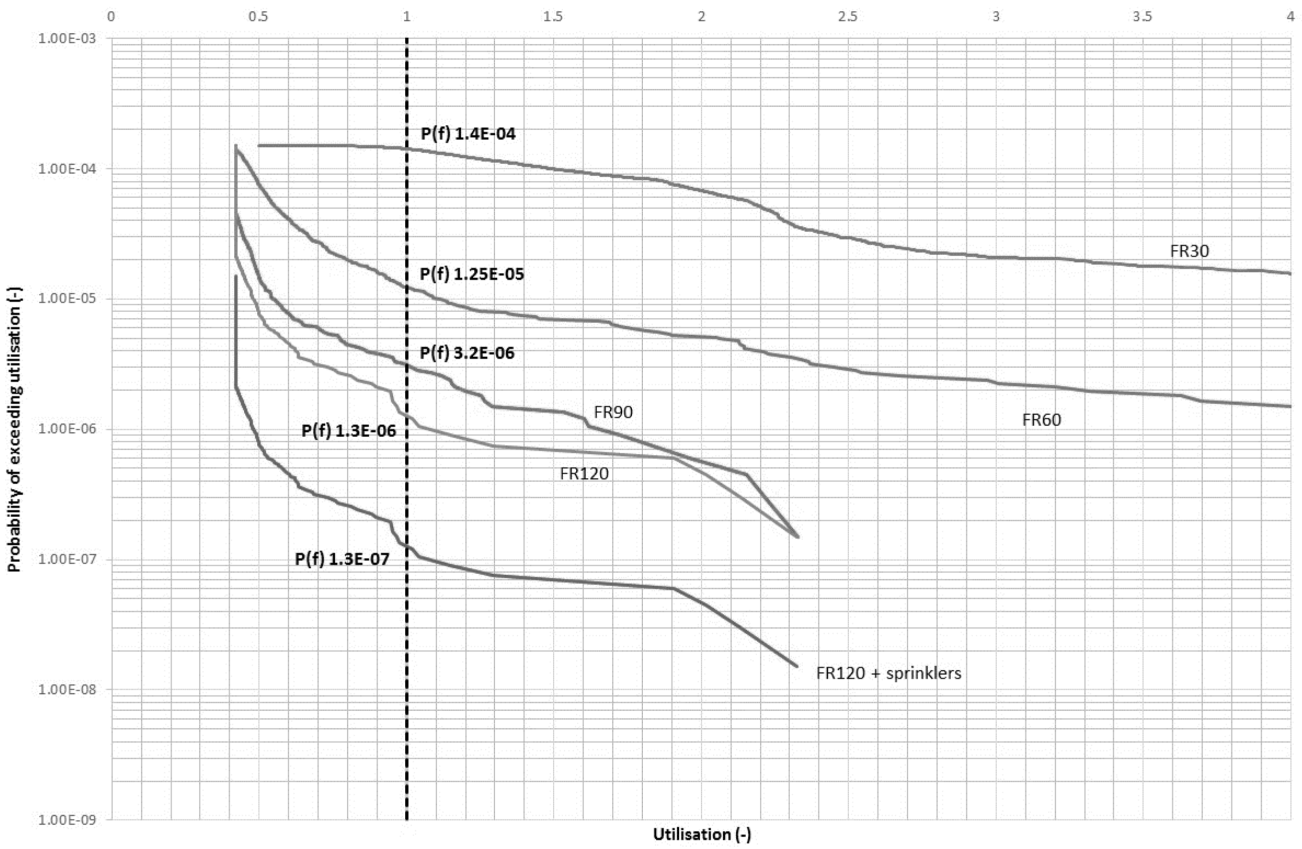

Figure 6 – Prob. of exceeding a given utilisation for different active and / or passive solutions

6. DISCUSSION

The results in Section 4.7 and the benchmarking outlined in Section 5 are discussed in differing contexts below.

6.1 ADB INHERENT SAFETY TARGETS

For a straightforward office building, with uncertainty limited to idealisations of the fire conditions, tentative failure probabilities for isolated steel elements afforded different fire resistance solutions have been determined. These generally show good agreement with the cost-optimisation safety targets noted in the JCSS Probabilistic Model Code, except for taller buildings, where sprinklers would commonly be included as part of the fire safety solution(s).

For the four cases investigated (A – D), there is approximately a linear relationship between height and reliability index (β), as shown in Figure 7. This is subject to the fire resistance solution being commensurate with height and according to the guidance within ADB.

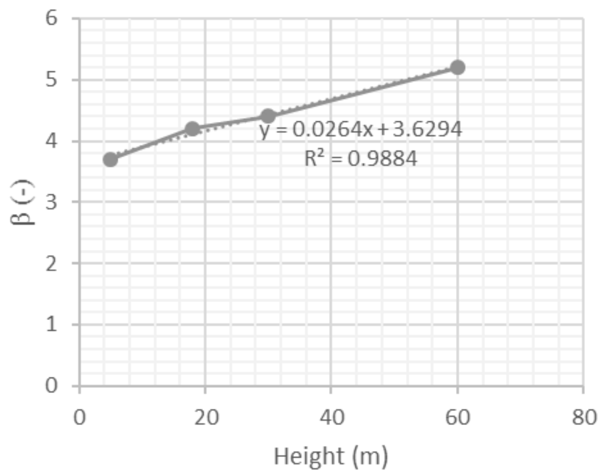

Figure 7 – Tenative relationship between height and reliability index for a straightforward ADB office

Practically, the relationship between height and reliability index presented in Figure 7 cannot be extrapolated before quickly converging on a safety target that is unfeasibly small. Therefore, for 'special structures', it may be prudent to impose an upper bound safety target.

6.2 BASIS OF SOCIETAL ACCEPTANCE

By adopting the JCSS (cost-optimisation) safety targets, it can be seen that the resulting fire resistance solutions are inconsistent with those that would be proposed within the prescriptive guidance to the Building Regulations (Approved Document B). Tentatively, they would support a reduced investment in safety measures. This is largely consistent with the findings of Kirby, et. al. when developing BS 9999, where office fire resistance proposals are typically less onerous than those recommended in Approved Document B. The latter, however, has significant precedent, as it has been widely used for straightforward buildings for a number of decades. The absence of change to the guidance therein could be interpreted as an acceptance of the safety levels achieved. This has been the basis of the development of other methods that seek to define the safety targets for tall apartment buildings [13]. Therefore, as is noted in ISO 2394, cost-optimisation does not guarantee that minimum societal safety expectations are attained. A logical extension of the work herein would be to check the compatibility of the cost-optimisation targets with minimal societal targets, informed by metrics, such as the Life Quality Index.

6.3 ROBUSTNESS

Despite the good intentions of EN 1990 to permit the adoption of transparent safety targets via Annex B, there is ambiguity regarding the safety levels achieved in a whole or sub-frame context. Whilst safety targets are set for isolated elements and sub-frames as a function of consequence, additional disproportionate collapse requirements result in additional 'factors of safety'. These can arise due to additional ties, notional removal methods, key element methods and systematic risk assessment.

The same principle could be considered for structural fire engineering, whereby the safety target for the structure must be fulfilled for fully developed fires without any adjustment for the likelihood of a significant fire developing when, for example, sprinklers are provided. However, generally, it is considered that an explicit safety target should be set without hidden safety margins. This introduces further complications in terms of defining what failure means for sub-frame or whole-frame assemblies.

6.4 TRANSIENT SAFETY TARGETS

Unlike sudden structural collapse, fire is a transient phenomenon that is often accompanied with forewarning. This alone means that there is reasonable grounds on which to challenge the relevance of ambient temperature safety targets when adopted or altered for the purpose of structural fire engineering assessments. The NFSC that is now inherent within Annex E of BS EN 1991-1-2 is premised upon a simple alteration to the EN 1990 ambient safety targets in cognisance of the fact that fire occurrence has an associated (low) probability. When approaching design with a 'fire resistance' mind set, this has credence. Fire resistance is a proxy for the performance required of elements such that they can withstand the burn-out of an appropriate realistic fire. Therefore, the performance goal is largely independent of time as the final outcome is a structure robust to the burn-out of an appropriately severe fire. In practice, however, the consequence of a fire induced structural failure is time-dependant. In most typical office situations, for example, the building will be progressively evacuated, meaning the risk of fatalities reduces with time.

What is fundamental, therefore, is that the probability of failure whilst a building is heavily occupied is very small. This potentially brings about a need for two life safety targets, one which defines the target for burn-out and another which requires that during the early evacuation phases premature fire induced structural failure has an exceptionally small likelihood. This is shown indicatively in Figure 8. The figure serves to demonstrate that for some types of building, e.g. high-rise, the burn-out and evacuation safety targets may coincide due to the impracticalities of evacuating tall buildings or due to the evacuation strategy being premised on refuge floors / 'invacuation'. In considering two life safety states, it suggests that reliance upon active measures alone (such as sprinklers) may be inappropriate as the failure probability of that single safety measure could be incompatible with safety targets for the evacuation phases. This is reinforced within typical prescriptive guidance whereby structures are typically afforded a minimum passive safety measure alongside active measures (e.g. 30 minutes fire resistance).

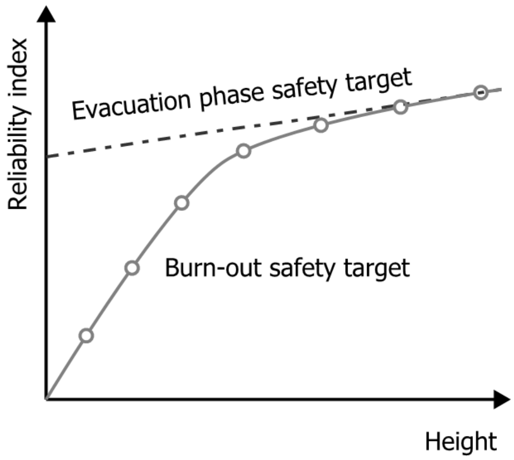

Figure 8 – Indicative relationship between height and reliability index for two life safety targets – evacuation phase vs. burn-out

7. CONCLUSIONS

The conclusions of the study presented herein are as follows:

- The paper has presented a novel probabilistic risk assessment approach, making use of Latin hypercube sampling to generate an array of possible fire conditions for a straightforward steel structure office building;
- These fires have been adopted to approximate the failure probabilities associated with different fire resistance solutions as would be common for differing heights of building;
- The study has allowed for the benchmarking of the outcomes against prescriptive guidance (ADB), leading to a tentative approximation of the inherent element failure probabilities as a function of height;
- The derived failure probabilities show reasonable consistency with those noted in the JCSS Probabilistic Model Code concerning cost optimisation; and
- Finally, the paper identifies a need for the distinction of two life safety targets for most buildings, i.e. one that distinguishes the burn-out requirement versus the evacuation phase requirement.

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